STATE OF THE ART—1961

Astrodynamics

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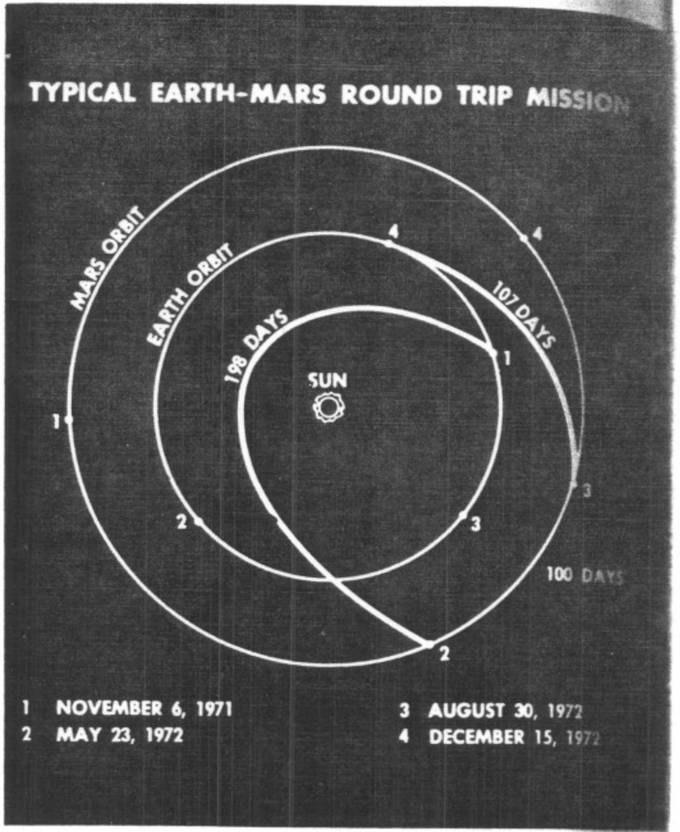

THIS year has seen a continuing acceleration in astrodynamic research and a consequent redoubling of the literature. A few more of the "old hands" of celestial mechanics have become more active in the field of astrodynamics, that is, in the practical application of celestial mechanics to astronautics; and, of course, there is the steady influx of newcomers to the field. It is a very healthy sign that an ever-increasing number of these newcomers are seeking postgraduate and even postdoctoral formal education in astrodynamics. Only through formal education taken hand-in-hand with practical ex-

STATE OF THE ART—1961

Communications and Instrumentation

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THE year 1961 saw a number of technical feats and developments that exemplify the considerable advances made in the state of the art of communications and instrumentation.

Venus Radar Bounce Experiment. This operation, performed again in the past year, was singularly significant in that it represented positive contact with another planet in our solar system. Further, it provided a considerable refinement in the accuracy of the Astronomical Unit, and was accomplished with a communications system composed of many elements which crowd the state of the art in performance. Two-hundred hours of valid recorded data resulted from the Venus-bounce experiment. Two months spent in reducing these data resulted in a figure for the A.U. of 149,598,500 plus or minus 500 km. There is every reason to believe that further data reduction and analysis perience can the astrodynamic competence of our nation's scientific community be improved.

It is also heartening to see fewer research papers having limited distribution within specific companies or organizations. By and large, astrodynamic research is of an unclassified nature, and it is incumbent upon the researcher to see that his ideas are viewed by his scientific colleagues. Such publications not only expose them to the light of public scrutiny and criticism, but allow others to build up their work.

We are no longer in the era of the alchemist who secretly advanced the cause of science. For an individual or a group to carry out worthwhile astrodynamic activity (both theoretical and applied) it is mandatory that they allow their work to be observed by their scientific colleagues, even if the time expended in this pursuit may seem wasted. There have been all too many examples of national programs being executed by newcomers to astrodynamics who have neither benefited from formal education in the field nor published their research —all to the detriment of the program for which they were responsible. Often they have been frightened "to let others see," for fear of losing a hard-won government contract because of adverse criticism. Fortunately, such barriers to progress are gradually dissolving due in no small way to the increasing competence and astrodynamic education of Army, Navy, and Air Force officers and NASA officials who have discretion in the award of such contracts and who monitor the contract once it has been let.

New Texts Helpful

Representative of the interest of the celestial mechanician in the relatively new field of astrodynamics are the two new texts in celestial mechanics published in the past twelve months. The first was Theodore Sterne's "An Introduction to Celestial Mechanics" (Interscience Publishers, $4.50) and the second was Dirk Brouwer and G. M. Clemence's "Methods of Celestial Mechanics" (Academic Press, $12.50). Although both these books deal mainly with celestial mechanics, they have enjoyed a wide circulation among astrodynamists and are recommended reading for anyone seriously interested in the field. Another fine book related to astrodynamics is I. Berman's "The Physical Principals of Astronautics" (John Wiley & Sons, $10.50). Soon to be published will be (CONTINUED ON PAGE 80)

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will reduce this uncertainty to plus or minus 150 km by the end of 1961.

The experiment provided other valuable information on Venus: It is either a highly specular reflector or it rotates at an extremely slow rate. Venus is a much better radio reflector than the moon.

Deep-Space Instrumentation Facility in Full Operation. The NASA's DSIF was completed in the past year and was demonstrated to have full operational capability. This achievement is significant because it provides this country with the capability to control and receive data from lunar and planetary spacecraft planned for the future. Successful operation of the DSIF worldwide net represents, further, an outstanding example of international cooperation, inasmuch as the Woomera and South African stations are operated by technical agencies of the Australian and South African governments.

High-Efficiency Communication Systems. The past year has seen considerable activity advancing the state of the art in the theory and mechanization of high-efficiency telecommunication systems of several kinds. Advances have been made in the areas of synchronization (CONTINUED ON PAGE 104)

Communication satellites, such as this developmental model being worked on by Bell Telephone Labs technicians, represented a focus for the state of the art of both communications and instrumentation last year. At least three different experimental communication satellites will be launched next year.

sufficient weight to the moon for the landing and return to earth. The two-shot approach, which will involve the docking of two space modules in orbit, or by rendezvous on the lunar surface, serves to divide the one-shot booster liftoff weight by a factor of 2 or more.

It is an accepted idea that interplanetary manned expeditions will require orbital docking of several space modules, even if the launch vehicles are of the Nova size. Hence, the early development of Saturn docking operations for the lunar mission appears to be a logical step.

The second decision will be on liquid versus solid propellants for Nova and Saturn vehicles. Both solids and liquids offer attractions, and problems. Liquid and solid Nova, for example, would weigh 8- to 30-million lb respectively, while corresponding weights for Saturn would be 4- to 10-million lb, respectively. High-energy chemical upper stages appear certain for either class of boosters, but the sizing of the upper stages is dependent on the modes of operation and choice of propellant for the boost phase. Eventually, nuclear or electric propulsion in upper stages will enter the picture; but at present, state-of-the-art materials and propellants are being considered, with no breakthroughs except, of course, the giant stride to stages and vehicles of large size.

The third decision, and perhaps most important of all, due to its effect upon the other two, pertains to the earth re-entry payload—whether it should be a one-man modified Mercury capsule weighing seven to 10,000 lb or a three-man Apollo capsule weighing 15,000 lb. The liftoff weight of the boost vehicle is almost directly proportional to the earth re-entry weight. The choice of the one-man capsule, therefore, would greatly reduce the booster weight, size, and development cost. A fully automatic one-man lunar-landing spacecraft can be developed in which the human occupant just goes along for the ride, so to speak, and is not required to accomplish any difficult tasks at lunar turnaround and checkout. Additional tasks can then be assigned to the astronaut which simplify the automatic system, such as manual control of the spacecraft during the lunar landing, as opposed to automatic control monitored from earth through a television link. In this manner the presence of a one-man crew can be expected to improve the reliability of a fully automatic device, without overtaxing the capability of the astronaut.

By contrast, the larger, three-man Apollo capsule, equipped with more scientific gear, will rely more heavily upon its crew for scientific observations and other functions, such as lunar turnaround and checkout operations. Obviously the larger, better-equipped payload is preferable, but it has the disadvantage of approximately doubling the launch-vehicle size, which would influence reliability, development time, cost, etc.

The one-man mission could be carried out with Saturn rather than Nova. However, the sheer loneliness of the astronaut on such a trip recommends the three-man capsule. The one-man lunar expedition is now thought too meager for a nationally sponsored project, and plans are accordingly being based on the three-man Apollo capsule. These plans will provide us much thought and work in the coming year. ♦♦

Astrodynamics

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volumes by Paul D. Arthur, John Nicolides, and others that will tend to round out and supplement the other texts in the field discussed in last year's survey article.

One can delineate some eight subdivisions within the broad field of astrodynamics: (1) Geometry and coordinate systems, (2) astrodynamic constants (including heliocentric, geocentric, lunar, planetary, and atmospheric constants), (3) orbit determination (both preliminary and definitive), (4) perturbations (including the n-body problem and nongravitational and relativistic effects), (5) orbit prediction (including both special and general perturbations), (6) applications of astrodynamic theory (including orbit selection and modification, low-thrust orbits and geocentric orbits), (7) observation theory and, finally, (8) attitude dynamics.

Each of these subdivisions will be briefly introduced here and one or two of the 1961 advances in each area will be highlighted. As in the case of the 1960 state-of-the-art article, the published research papers are so numerous that it is impossible to properly reference all of them. A special ARS Preprint (No. 2215), to be issued early next year, will include specific references and a more thorough analysis of them.

In the subdivision of geometry and coordinate systems, advances have been made in a number of graphical techniques, as well as in the development of procedures for coordinate transformations. The problems in this area include the proper choice of coordinates for specific systems, such as the choice of selenocentric or selenodetic lunar coordinates and the proper reference equinox for interplanetary transfer orbits. Work is presently afoot, albeit at a modest level of support, at various universities and scientific research laboratories.

Astrodynamic Constants Vital

Astrodynamic constants are now generally recognized as constituting a vital research area; 1961 has witnessed their continuing improvement. The tesseral harmonics (longitudinal variations) in the earth's potential field are sharing the attention received by the odd zonal harmonics last year; Kaula, Kozai, Izsak, and others are pioneering in this area. DeVaucouleurs has done an excellent survey of planetary and heliocentric constant determinations, adopting a value for each constant. A standard set has been proposed by Makemson, Baker, and Westrom that will hopefully set the precedent for further coordination of the entire field of astrodynamic constants.

Such was also the goal of a constants meeting held at Marshall Space Flight Center, sponsored by NASA, and of the work of O. W. Williams at the AF Geophysical Research Directorate, Hanscom Field, Mass. Determination of the solar parallax, the most inspiring of the active heliocentric constant research, has been advanced by electronic measurement of the distance to Venus by Jet Propulsion Laboratory and the Russians. The results of various determinations fail to agree within the bounds of their estimated errors, and the subject is by no means closed. Relatively little has been done in the area of lunar and planetary constants. Atmospheric constants, particularly the varying solar-produced density profiles of the earth and model planetary atmospheres have been actively studied. In connection with planetary atmospheres, an argument has arisen between Sinton and Kiess, Karrer, and Kiess on the abundance of nitrogen oxides in the Martian atmosphere. Although the argument has not been entirely resolved, it does appear that the more classical description of the Martian atmosphere remains in force.

The determination of preliminary orbits through Doppler-range-rate electronic measurements has been studied by a small number of scientists. The work by Armen Deutsch and the application of spectrographic binary techniques is particularly outstanding, and is being extended to elliptical and perturbed orbits by Koskela.

The definitive orbit problem finds a number of investigators rediscovering the differential correction. Others such as Van Sant, Herrick, and Kochi are making very significant contributions to the improvement of definitive orbit determination procedures. The universal set of variables developed by Herrick appears to be particularly promising both for definitive orbit determination and for orbit prediction. Joseph Siry and C. V. L. Smith of NASA and Wahl and Westrom of the National Space Surveillance System are both grappling with the problem of replacing subjective expert intuition by objective orbit-determination computer programs.

Within the framework of perturbation studies, Ellis and Diana together with Rabe, Hori, Moiseyev, and others have contributed significantly to the subject of the stability of the Lagrangian libration points. The question of this stability is far from solved, however, and the utility of these stable points for space missions still remains to be demonstrated. Of particular interest here are the reported observations of dust clouds at the Trojan points of the earth-moon system.

Among the areas of nongravitational and relativistic forces, the most popular subject has been that of electromagnetic effects. Bordeau, Donley, Serbu, and Whipple have published experimental data, while Chopra, Singer, Walker, Lo, and Cappellari and many others have made theoretical studies of these electromagnetic effects. Here certainly is a fruitful and exciting new field within astrodynamics in which many problems are yet to be attacked. A close runner-up in interest to the electromagnetic influences has been the radiation pressure studies, particularly those carried out by Levin, Bryant, Zadunaisky, et al. The Echo satellite proved to be an excellent test bed for such theories.

Although attracting much less interest than general perturbations in the area of orbit prediction, the subject of special perturbations—the numerical integration of individual satellite orbits—has been investigated. A number of techniques and routines have been devised by Michielsen and Kropp and Pines. O. K. Smith has considered the convergence of Newton's method for the solution of Kepler's equation, while Dunn and Newton have proposed the use of Green's function and a new variable, respectively, for use in special perturbations. Perhaps the research having the most promise in this area is that by Sperling, who is refining the varicentric method at the Marshall Space Flight Center.

The other procedure for orbit prediction is that of general perturbations—the analytical solution of orbits without a numerical integration specialized to any given orbit. This area of general perturbations still commands the greatest attention from theoretical astrodynamicists. Paraphrasing comments by R. H. Merson: The early treatments by King-Hele, Blitzer, Roberson, and others were adequate but had inherent singularities of the order of J_2e. Musen's Vanguard Satellite theory of 1959 was an improvement but was not suitable for $0.05 < e < 0.6$. Brouwer's treatment as well as Kozai's had critical inclination singularities (where $\sin^2 i = 4/5$), so that they could not well be applied to some early Russian satellites. Thus, in 1961, much research has been accomplished in the improvement of these theories and in the alleviation of the critical inclination difficulties. At the present time, it looks as if Herrick's rather unorthodox approach of using physical variables (especially his universal variables) may be advantageous and might offer the solution to the critical inclination problem, as well as problems arising when the eccentricity is nearly zero or unity. Blitzer has studied the coupling among various gravitational harmonics and has proposed a preliminary theory that was debated by Hori. In a slightly different approach, Musen has proposed the application of Strömgren's method to satellite orbits.

Orbit Treatment Advanced

Orbit selection and modification has also attracted the attention of a large segment of the astrodynamics community. Calculus of variations and other tools of optimization theory have been effectively employed in orbit selection and modification by Leitmann, Carstens and Edelbaum, Miele, Vargo, Faulkner, and many others. An interesting theory for interplanetary orbit correction has been developed further by Breakwell. A corrective thrust is determined only after an "information settling time" that is dependent upon the noise level of the position and velocity measurements, hence allowing a smoothing time for the best steady-state prediction.

Optimum low-thrust programming has also been under study, for example, by George Leitmann. The pertinent literature in the field has been surveyed by Gene Levin.

Applications to geocentric satellites, such as the error analyses of Duke, Goldberg, Pfeffer, Braham, and Skidmore, have been published in 1961. Gedeon and Pierce have completed a rather extensive study of interplanetary orbital transfers. There were surprisingly few research papers on the applications of lunar trajectories. It is expected that the Apollo program will stimulate a new rash of studies in this area, in particular the considerations of lunar "abort" trajectories a unified onboard navigational system (that is, useful on both the outbound leg to the moon and the inbound leg to the earth) needs more careful study. The question of whether the lunar navigational system should be done principally by the man onboard the vehicle or by a terrestrial tracking net remains unanswered, but is under study by Faunk and Mayer of the NASA Space Task Group.

Finally, applications to interplanetary orbits are receiving significant attention, particularly by Ruppe and Koelle at Marshall Space Flight Center. Already mentioned here has been Breakwell's work which together with studies by Ross, Lee, and Florence will better define the best interplanetary trajectories and the proper correction points. Projecting rather far in the future, we note that Cornog has reported on some of his research on interstellar navigation. Although no more than one or two such papers appear each year, this subject will undoubtedly deserve more attention as time goes on.

Research papers involving the application of astrodynamics to observation theory have been surprisingly numerous. These works run the gamut from Kissel's general study of real-time tracking to Gebel's investigation of a super-fast electrophotographic device for making daytime satellite observations. More conventional studies have been mounted in the use and improvement of instruments for obtaining position. Yatzunsky and Gurko have supplemented some of the prior work of Koskela in the investigation of the brightness of artificial satellites.

The subject of onboard observations has stimulated a number of papers concerning the possibilities opened up by astronomical observatories in space. In particular, F. G. Smith, Triplett and Deutsch have discussed the advantages to be gained by going outside the atmosphere. Deutsch, however, admonishes us to consider carefully before placing the Palomar telescope on orbit as he feels that most of the advantages could be gained either from earthbound observations or by observations made from high-altitude balloons.

Active attitude control lies more properly within the framework of navigation and guidance than in astrodynamics. Nevertheless, passive attitude dynamics, for example the nutational librations of the moon, do lie within the province of astrodynamics, and considerable research has been accomplished in this area during 1961. Burt and his associates in England have investigated the use of the gravity gradient to stabilize a toroidally shaped container, partially filled with fluid on orbit. Moran reported a more general solution of the dumbbell problem originally formulated by Klemperer and Baker in 1956. While DeBra and Delp studied the rigid-body attitude stability and natural frequencies of an object moving in a circular orbit. In this area we also find contributions by Roberson in the general formulation of the stability problem and Nidey, who has investigated the secular gravitational torque acting on a satellite traversing a circular orbit. This is related to Nidey's work on the astronomical observatory project at the Kitt Peak National Observatory.

Tidal Stability Use Dubious

It must be concluded that the use of natural tidal stability is not very promising except for certain very specialized situations.

A word should be said in conclusion about the educational aspects of astrodynamics. Important as it is to increase the number of formally educated specialists in astrodynamics, it is perhaps even more vital to insure that all space scientists are exposed to astrodynamics as a portion of their basic training. Unfortunately, there are all too few undergraduate programs in astrodynamics to serve such a requirement. The activities of Yale, Berkeley, Cincinnati, and many other institutions possessing competent celestial mechanicians are primarily centered at the graduate level. The UCLA program, consisting of four undergraduate and four graduate astrodynamics courses and offered by a staff of three astrodynamists, is presently the only complete undergraduate and graduate program offered. Furthermore, the 200–300 students participating in the UCLA program each year represent nearly 99% of the total astrodynamic educational output of the country. It is to be hoped that other universities will soon come to recognize the importance of a balanced graduate curriculum executed by a faculty of formally educated and trained astrodynamists. With the appointment of Professor Samuel Herrick to its staff as visiting professor for the coming year, MIT is pioneering this very concept. ♦♦